

## Reverberation Time, Feasibility for Weapons Fire Range Estimation

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### ABSTRACT

*Localization of an acoustic blast source in urban battle spaces is frequently complicated by multiple arrivals resulting from reflections within the acoustic environment. Temporal windowing can be used to isolate the direct arrival in situations where a direct path between source and receiver exist. However, if the source is located around a corner from a receiver the first arrival would lead to an erroneous source location estimate. These complications have prompted the authors to perform initial measurements of reverberation in a semi-urban environment. These measurements will assess the salience of reverberation as a means for estimating range to a blast source. Classical studies in room acoustics characterize reverberant spaces by their reverberation time, the time necessary for a diffuse field to decay 60 dB in level (or another suitable decay amount). Other subtleties, such as the rate of decay and the effect of coupled spaces, allude to the complexity of the environment within which the recordings were made.*

### INTRODUCTION

Sniper localization is of critical importance to armed forces around the world. Acoustic localization processing based on a muzzle blast and shock wave is robust, provided a direct path from the noise source to the measurement receiver exists<sup>1,2</sup>. Because of this direct path, localization is feasible in a suburban environment when the sniper localization system is collocated with the sniper's target. However, if a suburban convoy's detection vehicle is not the target, a direct path may not exist between the sound source and the microphone. Similarly, with fixed or mobile distributed microphones the acoustic event may occur a large distance from some of the microphones. This situation has been addressed through the use of time reversal processing to localize the source, but models of the environment are necessary with this technique<sup>3</sup>. In these cases, the first arrival at the microphone will not represent a direct path signal, and the direction of the first arrival is unlikely to represent the direction of the sound event.

This work considers the acoustic decay characteristics of a suburban environment<sup>4,5</sup>. The intent is to create an additional metric for received signals that can be used to assess the viability of the microphone for localization. In the event that the decay time is extremely short, the likelihood of the event having occurred locally is high. If the decay time is longer, the event probably occurred at a greater distance and the possibility is greater that no direct path exists between the event and the microphone. This is intuitive with human perception; consider a car backfiring several blocks away. An observer will know that the event is not in her immediate vicinity and that precise localization is unlikely based on the characteristics of the rise time and decay time. If the car backfires on the same street as the observer, rapid rise and decay times provide confidence that the event has been localized accurately.

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### MEASUREMENT AND PROCESSING TECHNIQUES

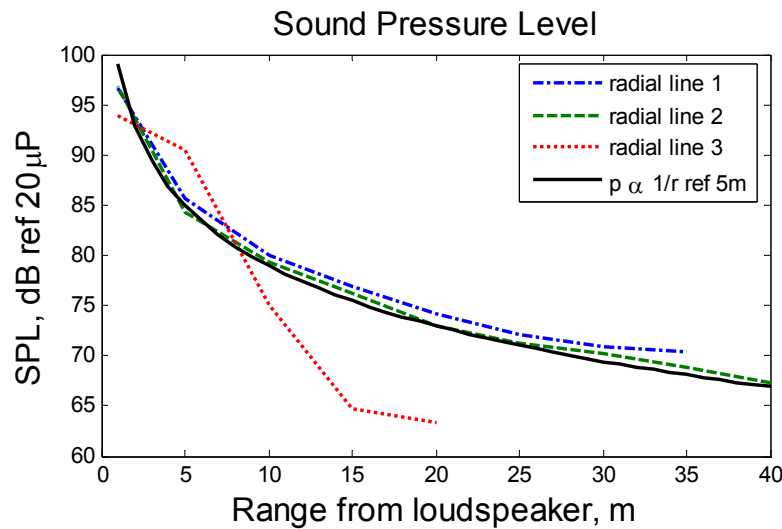
Measurements were made between three buildings in a suburban environment, Figure 1. The source was located near a point of entry for one of the buildings and the microphone was moved to a variety of ranges on three lines. For each radial direction the loudspeaker was oriented to face the microphone but the loudspeaker location was otherwise unaltered. The radial direction 3 required that the microphone be placed adjacent and behind a wall which obstructed the direct path from the source to the microphone.



**Figure 1. Environment used for reverberant decay measurements. The red dot represents the loudspeaker location and the radial lines represent the microphone ranges. Radial line three intersects a protruding wall.**

The source signal consisted of a linear sweep chirp from 50 to 5000 Hz that was broadcast with a commercial amplifier, Crown CE2000, and three cone loudspeaker box, KLH9912. The chirp signal is advantageous because of the control on frequency content and was selected because it is less disruptive to building occupants than a rifle source. However, a gun fire event would provide a better pulse signal with significantly higher peak pressure levels. The sound pressure level at 1 meter from the loudspeaker was 96 dB as measured on the ½ inch free field microphone, BK4942, connected to a preamplifier, SRS560. National instruments hardware, pci6221, and software, LabView, were used to acquire the data and to average responses. The averaging was affected by wind fluctuations that result in apparent sound speed shifts during each measurement, thus causing temporal stretching of the chirp signal. Alignment was performed on sequential measurements by cross correlating, selecting the peak delay, and shifting each new measurement before averaging. Most of the locations represent an ensemble average of 20 chirps but a few used 10 or 30 depending on the ambient noise levels at the given location.

Each ensemble average is then calibrated and filtered to remove noise that is out of band. The resulting pressure signals follow a range dependence of  $1/r$  for two of the measurement directions, Figure 2. The predicted line deviates slightly at the near ranges because of near-field effects of the 1 meter tall loudspeaker box and its image. Radial line 3 does not follow the trend; at five meters the microphone was adjacent to a small outwardly jutting wall, thus one would expect a pressure doubling effect. At 10 meters and beyond the microphone was obscured by this wall causing a significant pressure reduction<sup>6</sup>.



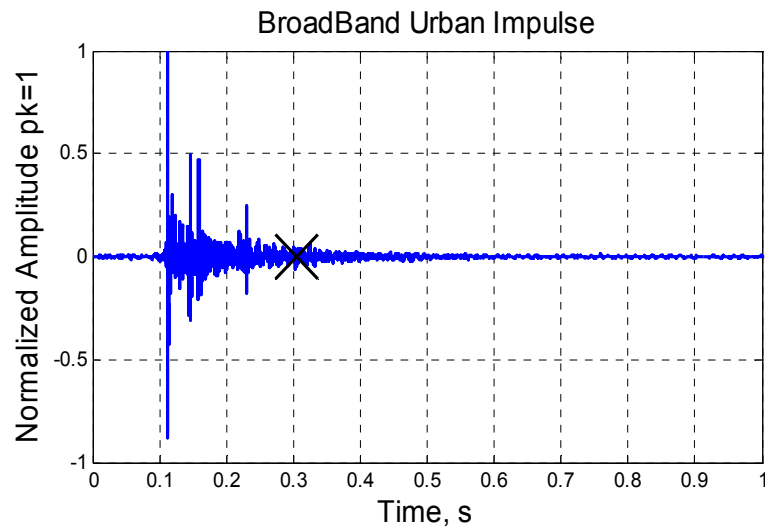
**Figure 2. Overall sound pressure level of the recorded chirp signals as measured on three radial lines.**

The pressure chirp measurements are then cross correlated with the source chirp to produce an estimate of the impulse response<sup>7</sup>. This impulse response provides an effective representation of the suburban environment that is then used to compute the decay response of the system. The blast event from a gun will create a strong impulsive pressure signal that can be used to compute a decay curve directly and will not require cross correlation. The decay time is computed by reverse integration of the pressure squared impulse response<sup>8</sup>. This is accomplished with a cumulative sum of the square of the impulse response bins in reverse order and therefore requires few digital computations. The resulting decay curves are then analyzed to determine the decay characteristics.

## ANALYSIS

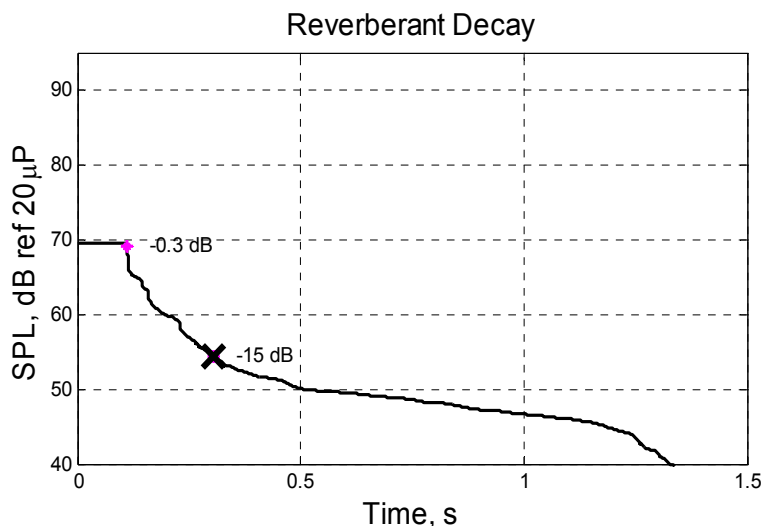
Analysis of the impulse responses indicate that environmental noise will play a critical role in the accuracy of reverberation time calculations. An experimentally derived impulse is shown in Figure 3. The peak amplitude is a result of the direct acoustic path, while the subsequent arrivals are related to reflections from the ground and surrounding buildings. The impulse response decays 15 db in .2 s between the initial arrival and the “x” mark that approaches the noise floor of this impulse.

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**Figure 3. Estimated impulse response in a suburban environment. Microphone range is 30 m from source on radial line 2. The mark indicates the 15 dB decay point.**

The noise floor is further illustrated in the decay curve associated with the impulse response at the point where the decay curve levels off, Figure 4. In traditional room reverberation studies this portion of the decay is easily identified since the decay has a linear form before the noise floor is reached. With the suburban decay curves shown here, the transition is less obvious since the decay curve resembles an exponential decay.

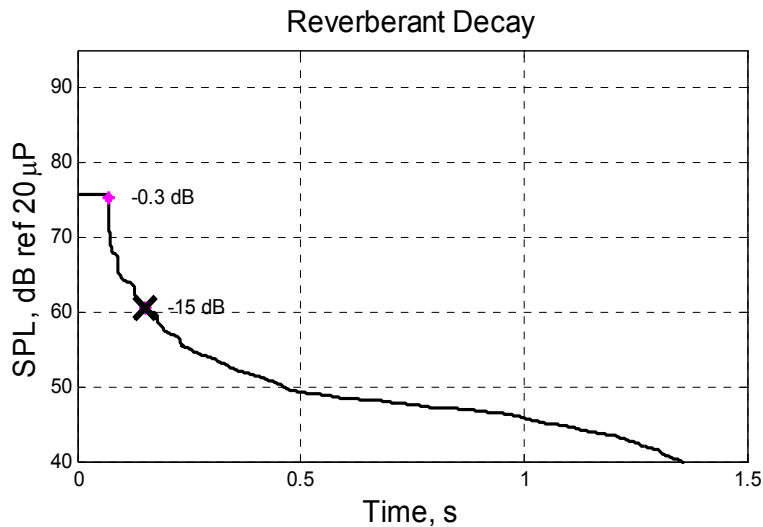


**Figure 4. Decay curve from impulse response. Microphone positioned 30 m from source on radial line 2. The flat portion of the curve below 50 dB is indicative of the noise floor. 15 dB decay time is .2 s.**

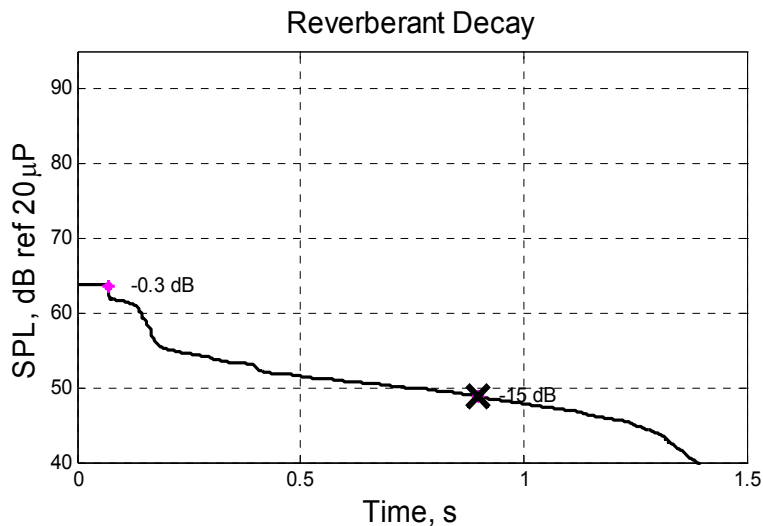
Historically reverberation time was defined as the time delay after turning off a specified sound source for that source to become inaudible. This is traditionally referred to as  $T_{60}$  in reference to a decay of 60 dB of the source signal. In the localization scenario audibility is not as important as consideration of the background noise levels of the environment. In this work a decay level of 15 dB referenced to maximum

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was used because this represented a worst case of signal to noise ratio. The noise floor was approximately 50 dB in the measurement space after averaging due to the presence of building mechanical equipment. The loudspeaker source level at 1 meter was 95 dB and fell off as expected with increasing range such that at 25 meters the source level was 72 dB. Even with a 15 dB decay time it is difficult to compute the decay time for measurements made at long ranges. This parameter requires adjustment based on source levels and ambient noise conditions at the microphone in the particular test location.



**Figure 5. Decay curve acquired at 15 m on radial line 2 illustrating the exponential shape to the logarithmic decay curve. Also note the jagged nature indicating that only a few arrivals occur during the first 100 ms. 15 dB decay time is .1 s.**



**Figure 6. Decay curve acquired at 15 m on radial line 3, a position obscured from the source by a wall. The initial drop is due to the diffracted path and the second is due to reflections off adjacent buildings. 15 dB decay time is .8 s.**

The decay curves generally do not assume a linear decay form as is typical for enclosed spaces, Figure 5 and Figure 6. Instead the direct signal is received followed by a brief delay before the echoes begin to arrive. Linear and exponential curves were fit between the start of the decay and the point where the

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decay reaches 15 dB below the peak level. A more complex fitting technique has potential to provide additional information about the character of the decay and environment, but has not been implemented successfully. Instead, a simple point pick was justified based on simplicity and accuracy of the result. The single point pick technique has the potential to introduce error when only two or three reflections are present, a situation that occurs when the microphone is near to the source. However, the reverberant environments of interest in this work will have longer source receiver ranges and a simple decay point selection will be accurate provided the noise floor is taken into consideration.

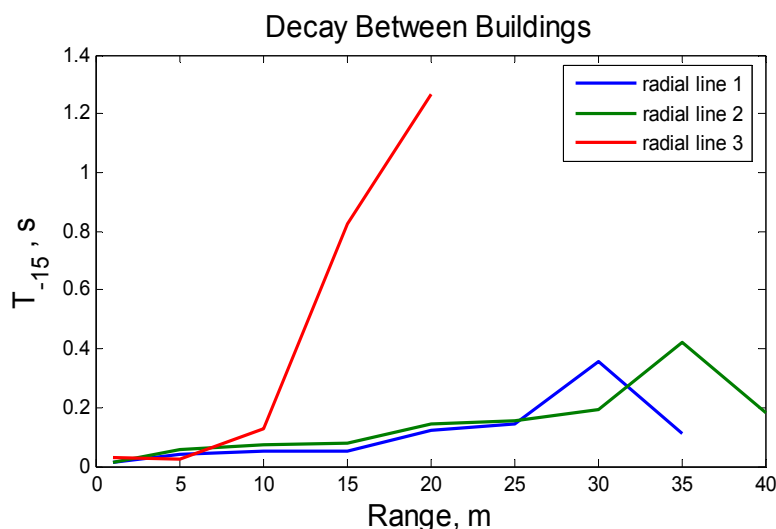


Figure 7. Decay time for 15 dB attenuation from the peak level as a function of range.

## CONCLUSIONS

The decay times increase with range from the sound source as expected, Figure 7. The decay values near the maximum range of each radial line are probably influenced by ambient noise and have a higher likelihood of being inaccurate. The decay time alone provides some indication of distance from source to receiver, but will depend on the environment. Additional clues are available through analysis of the shape of the decay curves, although this would require large data set to statistically determine the relationship between the fit parameters and the environment. Decay times associated with gunfire blasts in suburban environments seem a likely candidate to predict the existence of a direct acoustic path or whether the blast recording is a result of reflections only.

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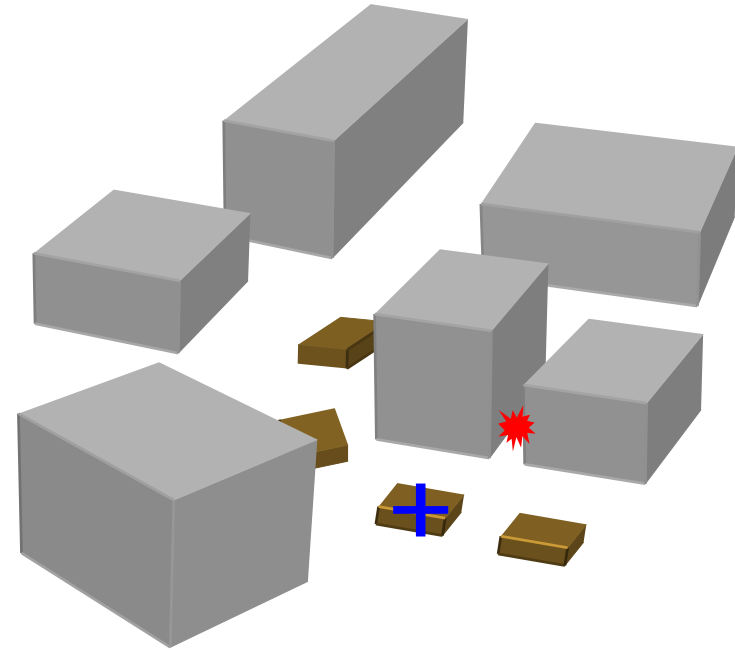
October 10, 2006



# Introduction, Direct Path Localization



- The Army seeks capabilities to **localize snipers** in urban battle spaces.
- Microphone arrays with appropriate processing will localize a sniper event based on the shock wave and muzzle blast, **provided a direct path exists** from the sniper to the microphones and the first arrival is isolated.
- Compact arrays effectively determine the direction of arrival, with **limited range information**.



★ Sniper fire event

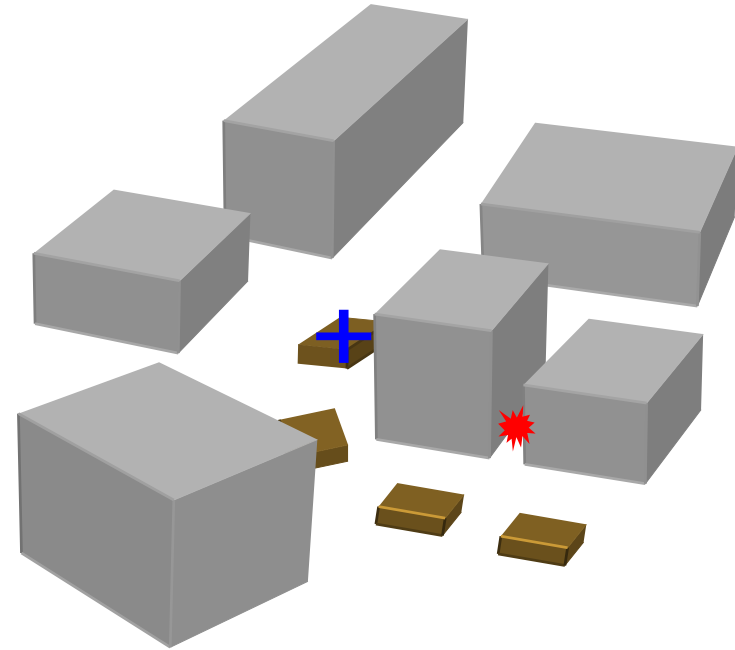
+ Microphone array



# Introduction, Ambiguity Without Direct Path



- ***Direct path may not exist***, leading to erroneous localizations.
  - e.g. A convoy's detection vehicle may not be the target.
  - e.g. Sensor density may not provide complete coverage of all areas of interest
- ***Diffracted path*** may be useful, but provides time delays greater than the vector distance.
- ***Echoes*** will lead to erroneous locations when a direct path does not exist.



\* Sniper fire event

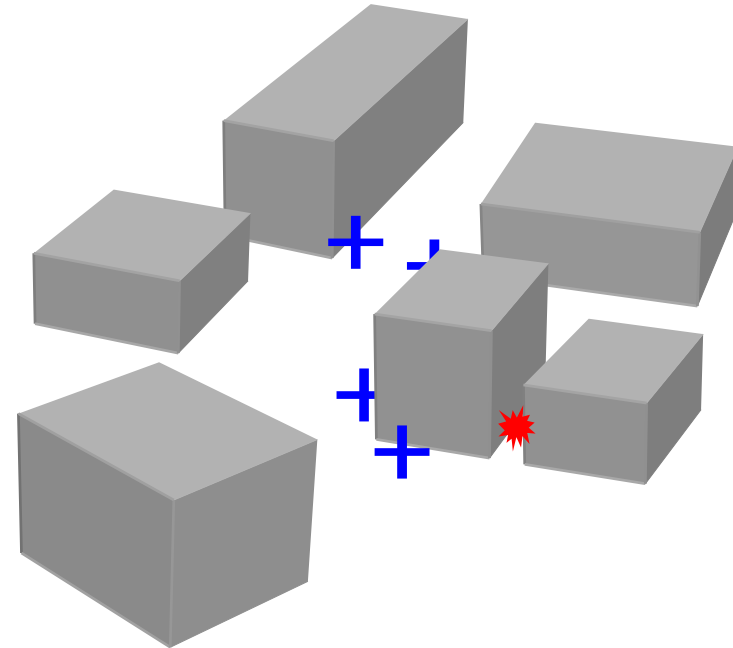
+ Microphone array



# Introduction, Distributed Arrays



- ***Can the data from a single channel be used to assess the effectiveness of the channel?***
  - i.e. Does the reverberant quality of a single channel indicate if the data is appropriate for inclusion in the network signal processing?
- Decay time is proportional to the range.
  - Brief decay time indicates the event distance is close.
  - Extended decay time indicates the event distance is far.
- ***Decay time (Reverberation time) provides clues to the viability of the signal for localization and possibly an estimate of range.***



★ Sniper fire event

+ Microphone



# Measurement Environment



Measurements were made between three buildings in a semi-urban environment.





- Large reflecting boundaries
- ..... Small reflecting boundaries
- # Height of building in stories



# Measurement Equipment Locations



Measurements were made between three buildings in a semi-urban environment.

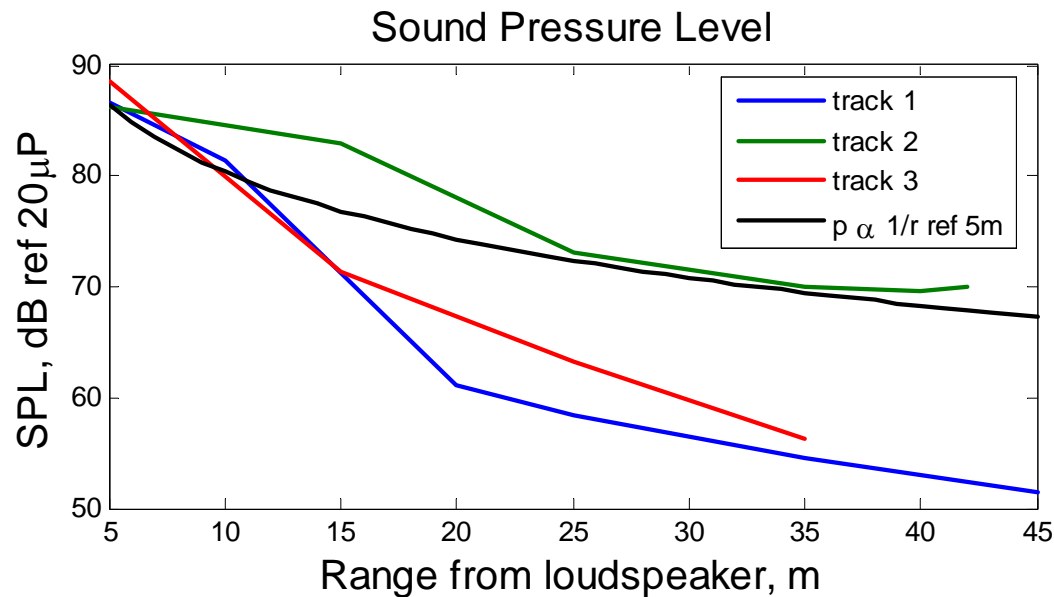
-  Loudspeaker box with three radiators.
-  Microphone locations
  - Track 1: 5, 10, 20, 25, 35, 45 meters (obstructed by building corner > 17 m.)
  - Track 2: 5, 15, 25, 35, 40, 42 meters (unobstructed)
  - Track 3: 5, 15, 25, 35 meters (obstructed by an outcrop > 6 m.)
-  Radial measurement tracks
-  Noise sources from building mechanicals.



# Processing



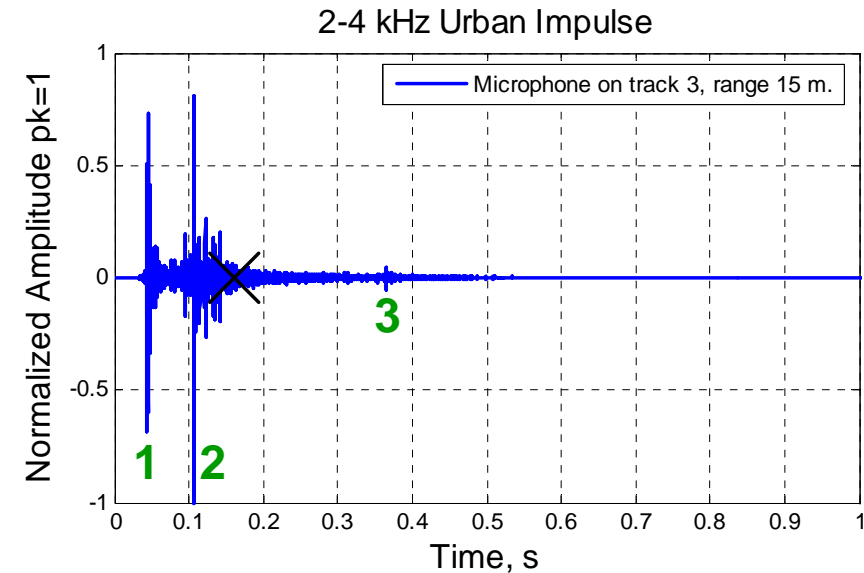
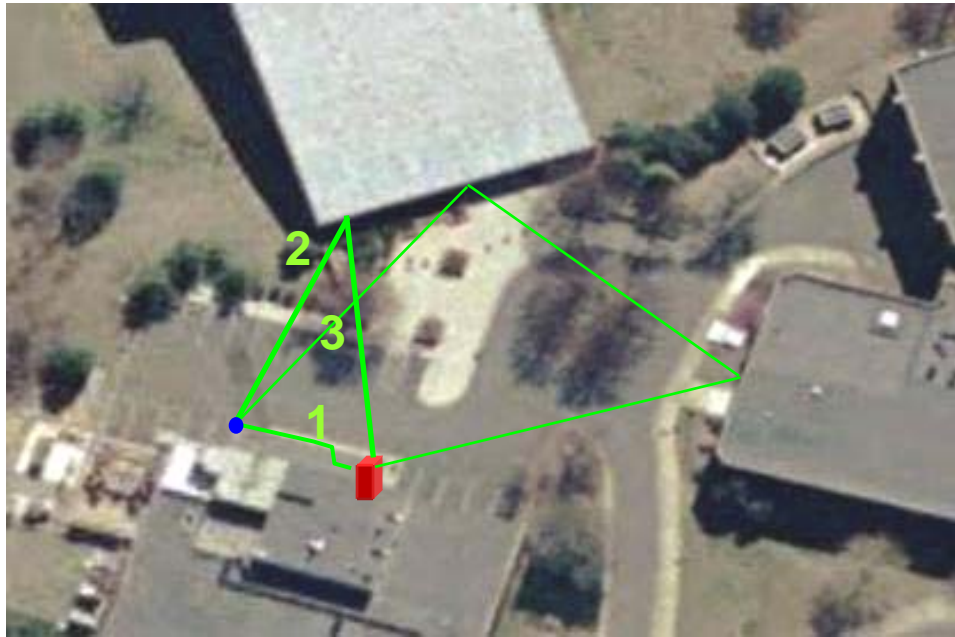
- Source signal.
  - Ideal source is impulsive blast, but too disruptive to building occupants.
  - Instead a 1 second chirp from 50 to 5000 Hz is used and post processed using cross correlation to estimate the impulse response.
- SPL 87 dB at 5 m (ref 20  $\mu$ Pa)
- Signal to noise was improved by averaging 100 chirps for each location.
- Data is high pass filtered at 2 kHz to reduce the effects of low frequency noise.



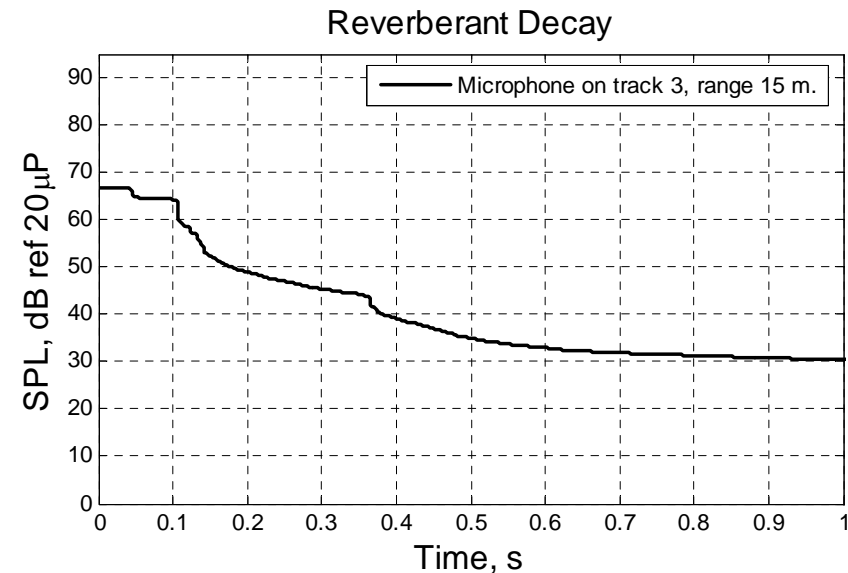




# Processing Results, location I (Moderate Obstruction)



- Geometric Considerations
  - 1<sup>st</sup> path is diffracted around a small outcrop.
  - 2<sup>nd</sup> path is reflected off of facing building.
  - 3<sup>rd</sup> path is a result of multiple reflections.
- Impulse response estimation from chirp.
- Decay curve generated from the **Schroeder reverse integration** of the impulse response.
  - First drop occurs after diffracted arrival.
  - Second and third drops occur after delayed echoes.
  - At long times the curve flattens due to ambient noise.

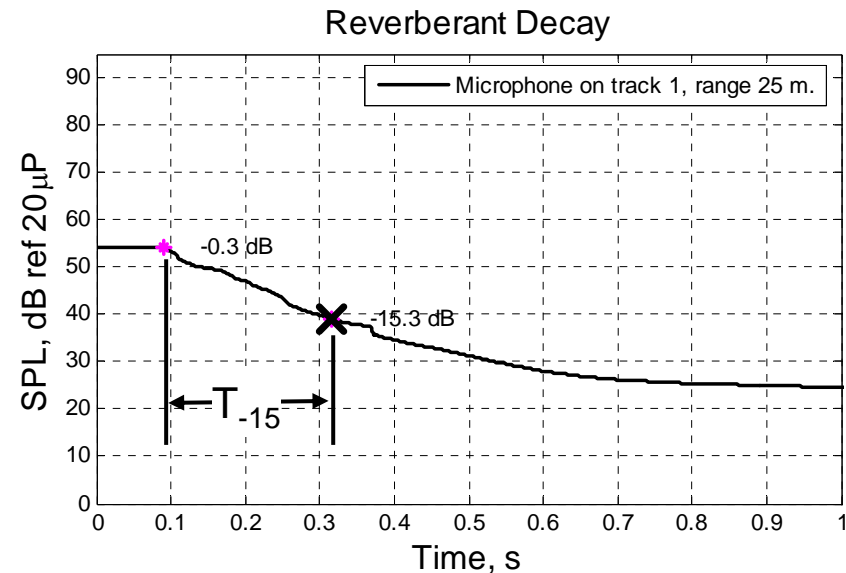
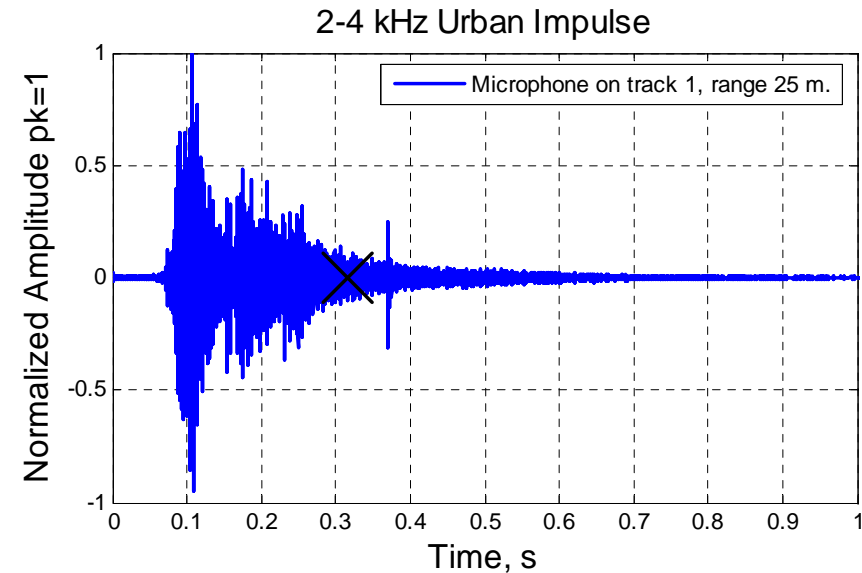




# Processing Results, location II (Large Obstruction)



- $T_{-15}$  = Decay time to reach 15 dB of attenuation is used instead of perceptual reverberation time,  $T_{60}$ .
  - Linear curve found for enclosed spaces is less apparent.
  - Early echoes are apparent and modify the consistent decay form.
  - With sources much louder than the ambient noise lower decay values could be used.
- Measurements with direct line of sight yield much shorter reverberation times.





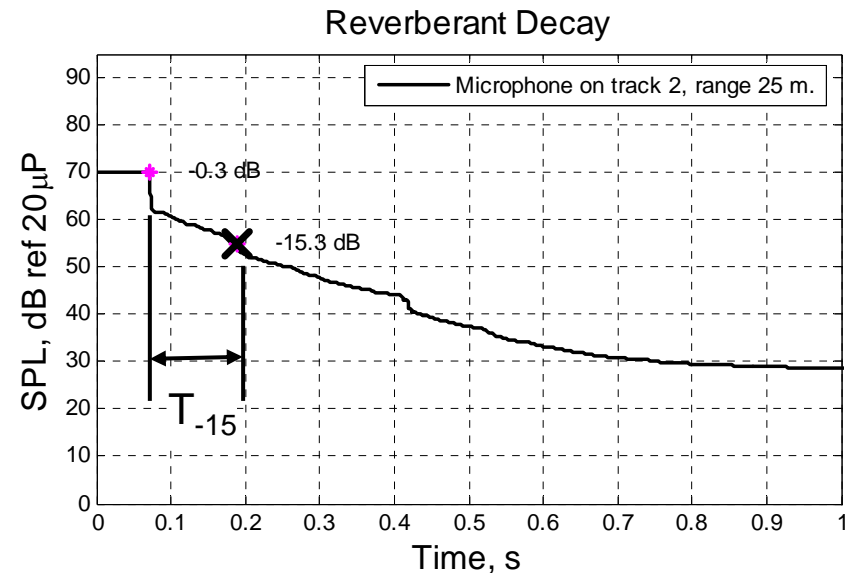
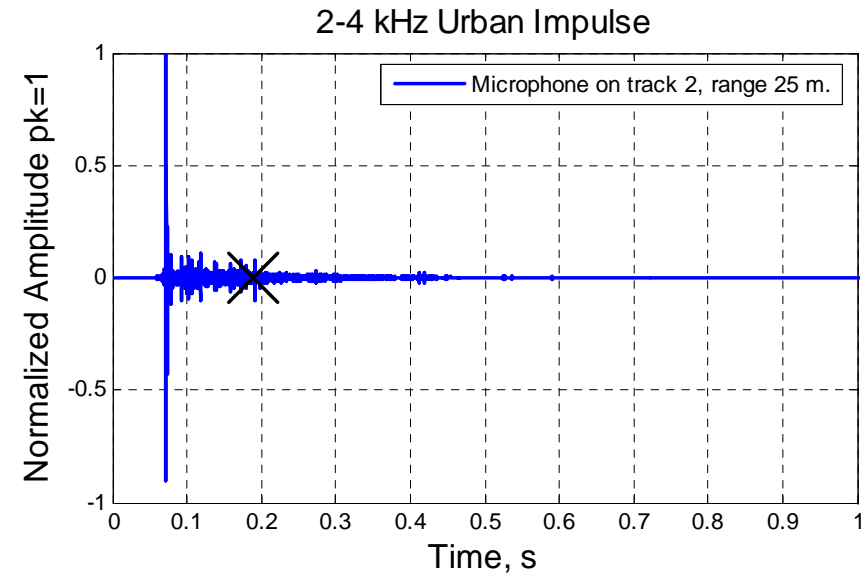
# Processing Results, location III (Direct Path)



- $T_{-15}$  = Decay time to reach 15 dB of attenuation is used instead of perceptual reverberation time,  $T_{60}$ .
  - Linear curve found for enclosed spaces is less apparent.
  - Early echoes are apparent and modify the consistent decay form.
  - With sources much louder than the ambient noise lower decay values could be used.
- Measurements with direct line of sight yield much shorter reverberation times.



Libbey, Reverberation





# Conclusions



- Generally, decay time increases with range.
  - Anomalous responses occurred near distant wall on Track 2.
- If the decay time is greater than an environmentally dependent threshold the data will not lead to accurate localization.
- Large obstructions in the direct path increase reverberation time dramatically.

